Performance Comparison of Current and Future Communications Systems in the EESS band

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Outline

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    - ECSS: European Cooperation for Space Standardization
    - CCSDS: Consultative Committee for Space Data Systems
    - SFCG: Space Frequency Coordination Group
- ESA Missions Communications Systems
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    - Current Schemes
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- Current ESA Ground Stations Configuration
    - High Data Rate Links
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Introduction

- Earth Exploration Satellites (EESS) band :8025-8400 MHz

- Typical orbit: circular, polar or near polar orbits with an altitude between 200-800 Km.

- These missions are usually bandwidth restricted (due to EESS band congestion) but not power limited.

- Depending on the data rate requirements, two architectures are common:

  - A TM subsystem that transmits both housekeeping and payload data

  - TM subsystem that transmits housekeeping information plus a dedicated high rate telemetry data downlink transmitter for the payload data.

Review of Standards - ECSS

ECSS recommends for channel symbol rates in excess of 2 Msymbols/s.

- Filtered-OQPSK (for all bands)
  - Filtered OQPSK, with baseband square-root raised-cosine (SRRC) filter and roll-off 0,5
- 4D TCM 8PSK (only for the EESS band) with two possible efficiencies: 2 and 2.5 b/s/Hz and with the following filtering options:
  - Square root raised-cosine baseband shaping located prior to the modulator, with a channel roll-off factor of 0.5 (or 0.35)
    - » Used in association with a linear modulator and power amplifier or when the symbol rate to central frequency ratio is low.
  - Post-amplifier shaping using an output filter located at the output of the non-linear power amplifier. The output filtering should be obtained with a 4 poles/2 zeros elliptic filter.
    - » NRZ-like shaping is used in conjunction with a non-linear 8-phase modulator or when the symbol rate to central frequency ratio is high.

Review of Standards - CCSDS

This recommendation is under review at the moment

CCSDS considers:

- that SRRC filtered 4-Dimensional 8 PSK TCM (Trellis Coded Modulation) and some filtered OQPSK modulations spectra can meet the SFCG emission mask for symbol rates in excess of 2 Ms/s with acceptable end-to-end losses;

- that SRRC filtered 4D 8 PSK TCM offers better link performance than filtered Offset QPSK for the same or better bandwidth efficiency;

- that current technology allows implementing and processing of 4D 8 PSK TCM modulation at the rates required in the band;

CCSDS recommends:

- that a mission planning to use conventional modulation methods and occupying a bandwidth exceeding that permitted by the SFCG use 4D 8PSK TCM provided that in no case shall the occupied bandwidth of said mission exceed that permitted by the SFCG;

- The available efficiencies are 2, 2.25, 2.5 and 2.75 b/s/Hz.

- Recommendation is at the moment provisisonal

- "Modulation and coding techniques can be considered as bandwidth efficient when the ratio of the source bit rate over the channel symbol rate is at least 1.75"

- The emitted spectrum shall conform to the spectral emission mask below

Figure 1: Spectral Emission Masks
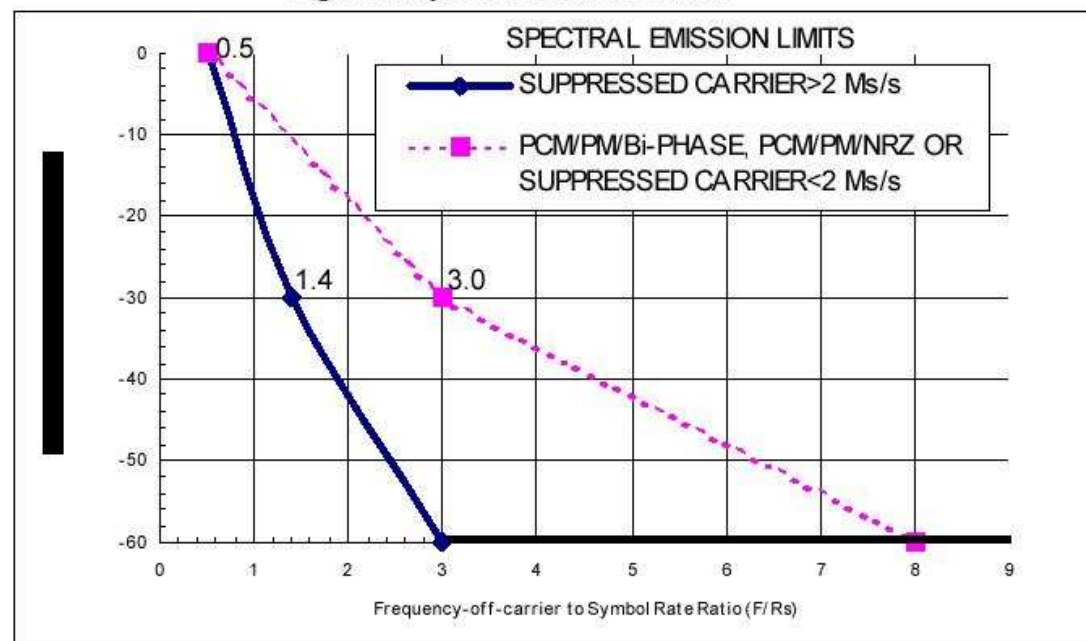
ESA Missions Review (I)

Planned ESA Programs in the EESS band:

- **Cryosat** (launch Sept 2005)
  - S-band TT&C transponder and X-band QPSK transmitter
  - Symbol Rate:100 Msps
  - Coding for the X-band link: Reed Solomon (255,223)
  - Filtering: Butterworth channel filter

- **Aeolus** (launch 2008)
  - S-band TT&C transponder and X-band OQPSK transmitter
  - Symbol Rate:10 Msps
  - Coding for the X-band link : RS (255,223)+ conv rate 1/2
  - Filtering: Elliptic channel filter

ESA Missions Review (II)

- **SMOS** (ESA-CNES joint project) launch early 2007
  - S-band TT&C transponder and X-band transmitter implementing 4D TCM 8PSK (2b/s/Hz)
  - Symbol Rate: 17 Msps
  - Coding for the X-band link: Reed Solomon (255,223)
  - Filtering: elliptic channel filter.
- **GOCE** (launch 2006) Operates only in the **S-band**
  - S-band transponder transmitting housekeeping and payload data.
  - Symbol Rate: 2 Msps
  - Modulation high data rate link: OQPSK
  - Coding: Reed Solomon (255,223)
  - Baseband Filtering: Square Root Raised Cosine (roll-off:0.5).

Modulation and Coding

Combinations of modulation and coding schemes that comply to the SFCG bandwidth efficient definition, "the ratio of the source bit rate over the channel symbol rate is at least 1.75" :

- OQPSK without coding
- OQPSK + RS (255,223) [1]
- OQPSK +conv 7/8
- 4D TCM 8PSK (2 b/s/Hz) without outer coding
- 4D TCM 8PSK (2.5 b/s/Hz) without outer coding
- 4D TCM 8PSK (2 b/s/Hz) + RS(254,238)[2]
- 4D TCM 8PSK (2.5 b/s/Hz) + RS(254,238)[2]

Note1: RS (255,223) and also RS (255,239) are compatible with the SFCG defined ratio
Note 2: Reed Solomon (254,238) as recommended by CNES. Also valid for RS (255,223) and non-shortened versions of the RS (255,239)

Modulation and Coding

Modulation	Filtering	Filter type	SSPA	Spectral efficiency (99%)
OQPSK	RF Filtering	Elliptic Filter order 4	No	1.48 b/s/Hz
OQPSK	Baseband Filtering	SRRC roll-off 0.5	No	1.57 b/s/Hz
OQPSK	Baseband Filtering	SRRC roll-off 0.5	SSPA in saturation	1.16 b/s/Hz
4D TCM 8PSK 2b/s/Hz	RF Filtering	Elliptic Filter order 4	No	1.63 b/s/Hz
4D TCM 8PSK 2b/s/Hz	Baseband Filtering	SRRC roll-off 0.5	No	1.56 b/s/Hz
4D TCM 8PSK 2b/s/Hz	Baseband Filtering	SRRC roll-off 0.5	SSPA in saturation	1.13 b/s/Hz
4D TCM 8PSK 2.5b/s/Hz	RF Filtering	Elliptic Filter order 4	No	2.04b/s/Hz
4D TCM 8PSK 2.5b/s/Hz	Baseband Filtering	SRRC roll-off 0.5	No	1.95 b/s/Hz
4D TCM 8PSK 2.5b/s/Hz	Baseband Filtering	SRRC roll-off 0.5	SSPA in saturation	1.4 b/s/Hz

- OQPSK with conv rate 7/8 or RS (255,223)
    - The efficiency with SSPA in saturation is reduced to 1.01 b/s/Hz
- 4D TCM 8PSK with RS(254,238)
    - 2b/s/Hz with SSPA in saturation is reduced to 1.06 b/s/Hz
    - 2.5b/s/Hz with SSPA in saturation is reduced to 1.31 b/s/Hz

BER Performance

Linear System

Modulation	Coding	BER=10^{-6}
OQPSK	Uncoded	10.5 dB
OQPSK	RS (255,223)	6.4 dB
OQPSK	Conv rate7/8	6.8 dB
4D TCM 8PSK 2 b/s/Hz	Uncoded	7.6 dB
4D TCM 8PSK 2 b/s/Hz	RS(254,238)	5.5 dB
4D TCM 8PSK 2.5 b/s/Hz	Uncoded	8.5 dB
4D TCM 8PSK 2.5 b/s/Hz	RS(254,238)	7.1 dB

Modulation schemes filtered with SRRC (α:0.5) and SSPA in saturation

Modulation	Coding	BER=10^{-6}
OQPSK	RS (255,223)	7 dB
4D TCM 8PSK 2 b/s/Hz	RS(254,238)	5.9 dB
4D TCM 8PSK 2.5 b/s/Hz	RS(254,238)	7.7 dB

Baseband versus Channel Filtering

- Baseband filtering
  - Low power filters
  - Low mass
  - Easy to implement
  - Provides a very limited in-band signal (improving the spectral efficiency)
  - Provides spectral regrowth when used in combination with an amplifier in saturation
- Channel filtering
  - High power filters
  - Bulky
  - Limit the spectrum in case of amplifier working in saturation
 - They do not improve the spectral efficiency

Future Modulation & Coding Techniques

Goal: Transmit the maximum information in the minimum occupied bandwidth and using the least transmit power.

- High order modulation schemes
- High performance codes
- Envelope equalisation
- Amplifier pre-distorsion
- In the frame of the ESA's Technology Research Programm, the MHOMS (Modem for High Order Modulation Schemes) Project, broadband satellite modem, has been developed:
  - Very high speed: target is up to 1Gbps
  - Challenging coding architectures, SCCC codes
  - Satellite channel non-linearity modulation resilient techniques
 - High order modulation schemes: 8PSK, 16-QAM, 16APSK, 32APSK, 64APSK

High Order Modulation Schemes

- High order modulation schemes like 8PSK and 16QAM are more efficient in bandwidth but sensitive to non-linearities caused by the amplifier in saturation

- Two non-linearity friendly higher order modulation schemes, 16APSK, 32APSK and 64APSK (ESA patented) could also be a solution

  • APSK is a power and bandwidth efficient constellation particularly suited for nonlinear channels

  • Linear channel performance very close (even superior) to 16-QAM

  • Circular concentric ring shape allows to minimize the HPA distortion effect

  • Nonlinearity effects are easy to pre-correct

  • ISI can also be mitigated by more advanced pre-correction schemes

4-12 APSK

4-12-20-28 APSK
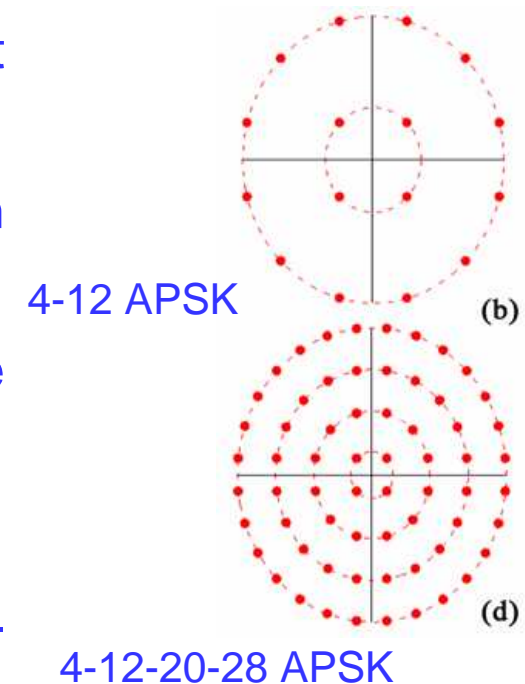
The Advanced MHOMS Forward Error Correction Scheme: SCCC

- Based on the serial concatenation of an outer 4-state systematic recursive rate ½ encoder punctured to rate 2/3, an interleaver and an inner 4-state systematic recursive rate ½ encoder with suitable puncturing to obtain the desired rate.

- The code design involves choosing the puncturing patterns matching the desired rate
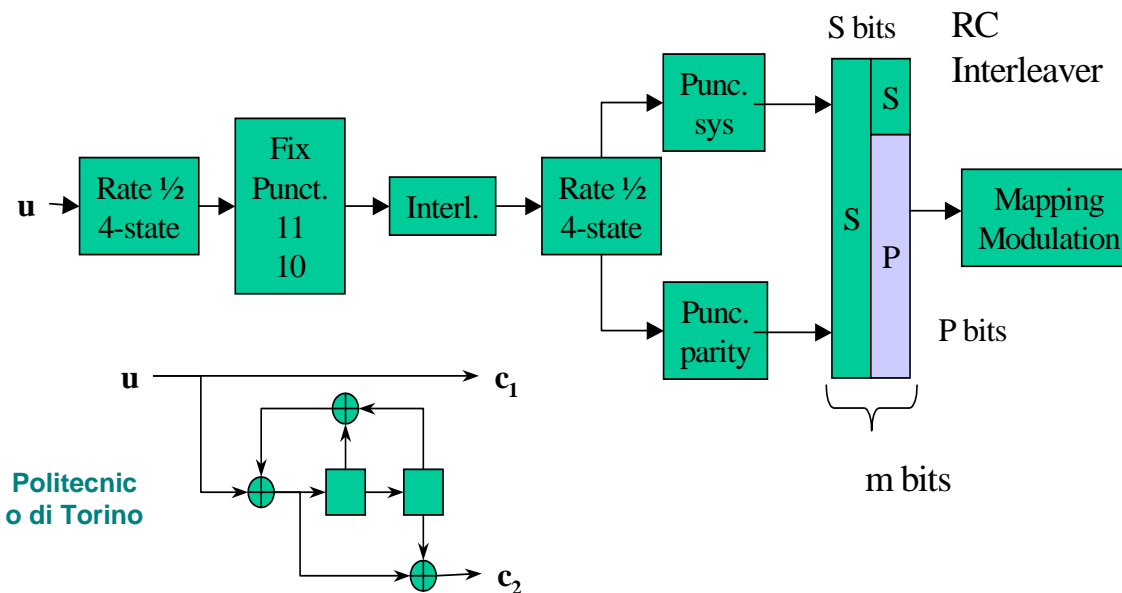
The interleaver length is designed in order to keep the block length on the channel constant to 8100 symbols regardless the modulation order or the code rate

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SCCC Characteristics

- A very evident advantage of the new scheme is its simplicity, owing to the use of two equal 4-state encoders

- Having the same encoder replicated twice also helps in the parallel architecture implementation needed to achieve high data rates

- A constant channel block length independent from the modulation order and code rate simplifies the receiver synchronization procedure

- Near-Shannon limit performance

- No patents on the code design

MHOMS supported set of spectral efficiencies

|		Es/N0	eta	K	I	N	m	Code Rate	Min Inf. Rate	Max Inf. Rate	K'	Ibest	eta'	Es/N0'	delta
					Nominal values							**Interleaver constrained**			
QPSK	1	-1.85	0.7254	5,876	8,817	16,200	2	0.36	557,795	142,795,466	5,917	8,880	0.7305	-1.81	
	2	-0.85	0.8659	7,016	10,527	16,200	2	0.43	655,835	167,893,874	6,957	10,440	0.8589	-0.90	0.91
	3	0.15	1.0254	8,306	12,462	16,200	2	0.51	784,042	200,714,870	8,317	12,480	1.0268	0.16	1.06
	4	1.15	1.2039	9,752	14,631	16,200	2	0.60	919,791	235,466,513	9,757	14,640	1.2046	1.16	1.00
	5	2.15	1.4012	11,350	17,028	16,200	2	0.70	1,063,081	272,148,803	11,277	16,920	1.3922	2.11	0.95
	6	3.15	1.6164	13,094	19,644	16,200	2	0.81	1,236,538	316,553,679	13,117	19,680	1.6194	3.16	1.06
8PSK	7	2.15	1.4012	11,350	17,028	24,300	3	0.47	1,069,963	273,910,518	11,277	16,920	1.3922	2.11	-1.06
	8	3.15	1.6164	13,094	19,644	24,300	3	0.54	1,234,370	315,998,619	13,117	19,680	1.6194	3.16	1.06
	9	4.15	1.8484	14,974	22,464	24,300	3	0.62	1,417,536	362,889,203	15,037	22,560	1.8564	4.18	1.02
	10	5.15	2.0958	16,976	25,467	24,300	3	0.70	1,598,534	409,224,727	16,957	25,440	2.0935	5.14	0.96
	11	6.15	2.3568	19,092	28,641	24,300	3	0.79	1,802,157	461,352,191	19,117	28,680	2.3601	6.16	1.02
	12	7.15	2.6299	21,304	31,959	24,300	3	0.88	2,005,780	513,479,655	21,277	31,920	2.6268	7.14	0.98
16APSK	13	6.15	2.3568	19,092	28,641	32,400	4	0.59	1,799,800	460,748,864	19,117	28,680	2.3601	6.16	-0.98
	14	7.15	2.6299	21,304	31,959	32,400	4	0.66	2,008,325	514,131,249	21,277	31,920	2.6268	7.14	0.98
	15	8.15	2.9133	23,598	35,400	32,400	4	0.73	2,216,944	567,537,766	23,517	35,280	2.9033	8.12	0.98
	16	9.15	3.2056	25,966	38,952	32,400	4	0.80	2,443,192	625,457,171	25,917	38,880	3.1996	9.13	1.01
	17	10.15	3.5053	28,394	42,594	32,400	4	0.88	2,669,440	683,376,576	28,317	42,480	3.4959	10.12	0.99
32APSK	18	9.15	3.2056	25,966	38,952	40,500	5	0.64	2,447,811	626,639,692	25,917	38,880	3.1996	9.13	-0.99
	19	10.15	3.5053	28,394	42,594	40,500	5	0.70	2,676,699	685,234,823	28,317	42,480	3.4959	10.12	0.99
	20	11.15	3.8111	30,870	46,308	40,500	5	0.76	2,910,771	745,157,274	30,877	46,320	3.8120	11.15	1.03
	21	12.15	4.1220	33,388	50,085	40,500	5	0.82	3,144,560	805,007,325	33,357	50,040	4.1181	12.14	0.98
	22	13.15	4.4370	35,940	53,913	40,500	5	0.89	3,385,891	866,788,024	35,917	53,880	4.4342	13.14	1.00
64APSK	23	12.15	4.1220	33,388	50,085	48,600	6	0.69	3,147,482	805,755,451	33,357	50,040	4.1181	12.14	-1.00
	24	13.15	4.4370	35,940	53,913	48,600	6	0.74	3,388,059	867,343,085	35,917	53,880	4.4342	13.14	1.00
	25	14.15	4.7555	38,520	57,783	48,600	6	0.79	3,634,763	930,499,369	38,557	57,840	4.7601	14.17	1.02
	26	15.15	5.0766	41,122	61,686	48,600	6	0.85	3,883,636	994,210,714	41,197	61,800	5.0860	15.18	1.01
	27	16.15	5.4000	43,740	65,613	48,600	6	0.90	4,117,425	1,054,060,765	43,677	65,520	5.3922	16.13	0.95

The meaning of each column in the table is as follows:

- E_s/N_0 Nominal signal to noise ratio thresholds from unconstrained Shannon Capacity Bound
- *eta* Nominal Spectral efficiency yielding the desired SNR according to the unconstrained capacity formula
- *K* Nominal information block size
- *I* Nominal interleaver length
- *N* Number of encoded bits
- *m* modulation efficiency
- Rate of the code (*K/N*)
- Maximum information rate, assuming 200 Mbaud over the channel
- *K'* Information block size obtained applying the constraints on the interleaver block size that derives from parallelism
- *I'* Interleaver size applying the constraints that derives from required parallelism
- **eta'** true spectral efficiency applying the constraints on the interleaver block size that derives from parallelism
- E_s/N_0' signal-to-noise ratio applying the constraints on the interleaver block size that derives from parallelism
- **delta** True signal to noise ratio step.

Simulated performance of the 27 spectral efficiencies (AWGN)
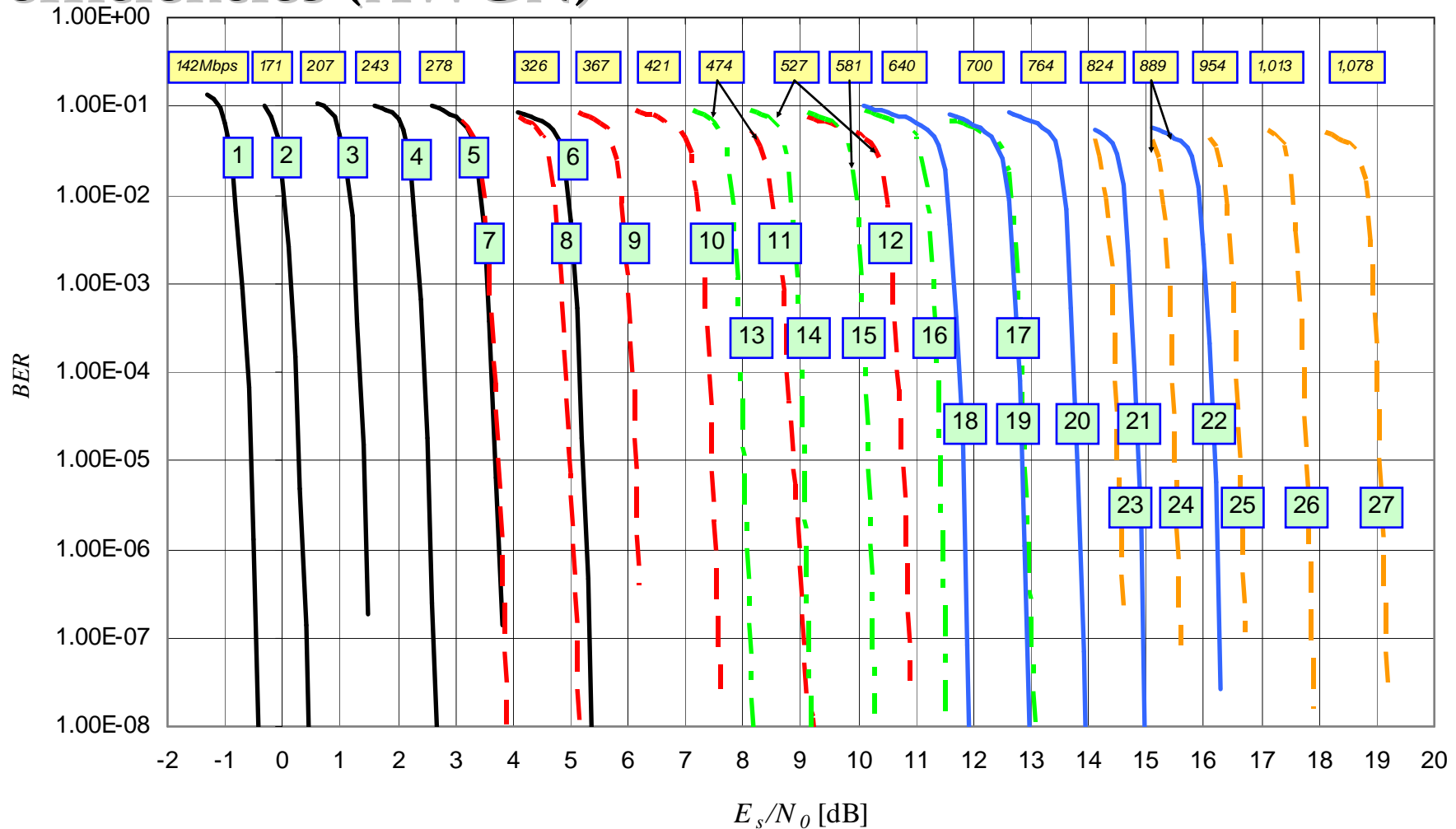
Performance comparison between MHOMS SCCC 8PSK and 4D-8PSK-TCM+RS at BER~10^{-9}
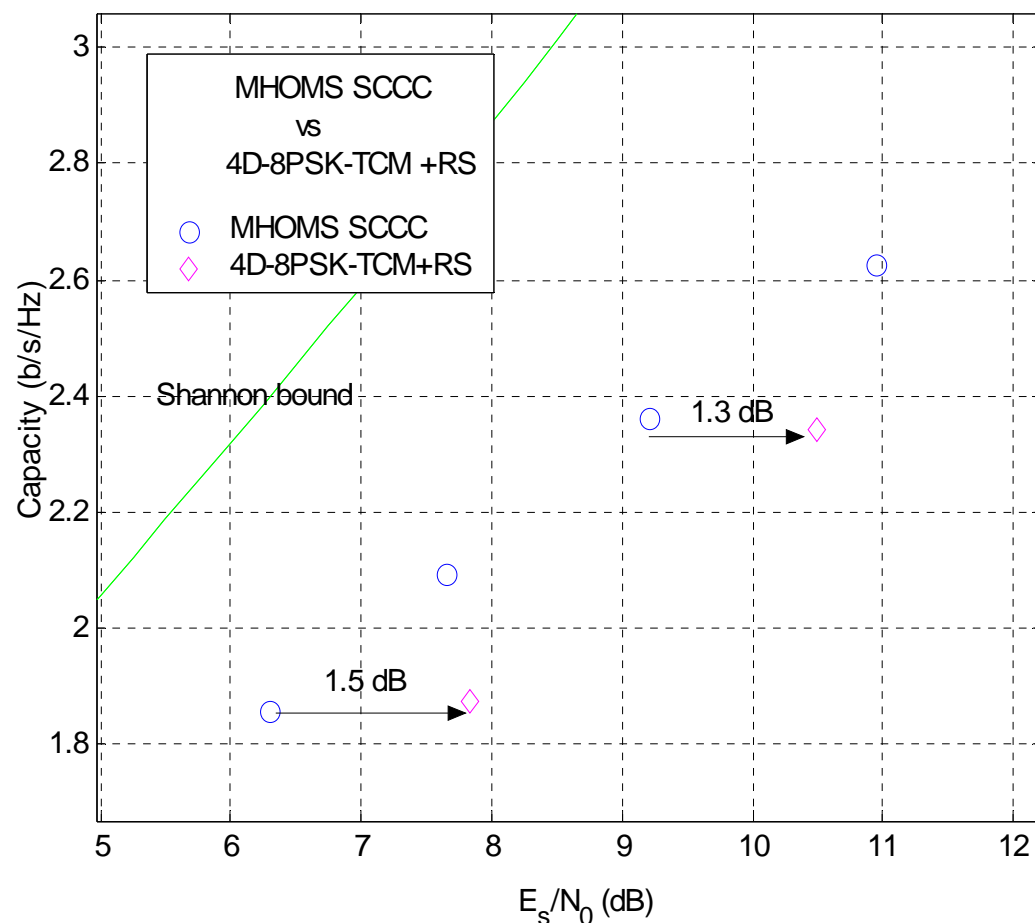
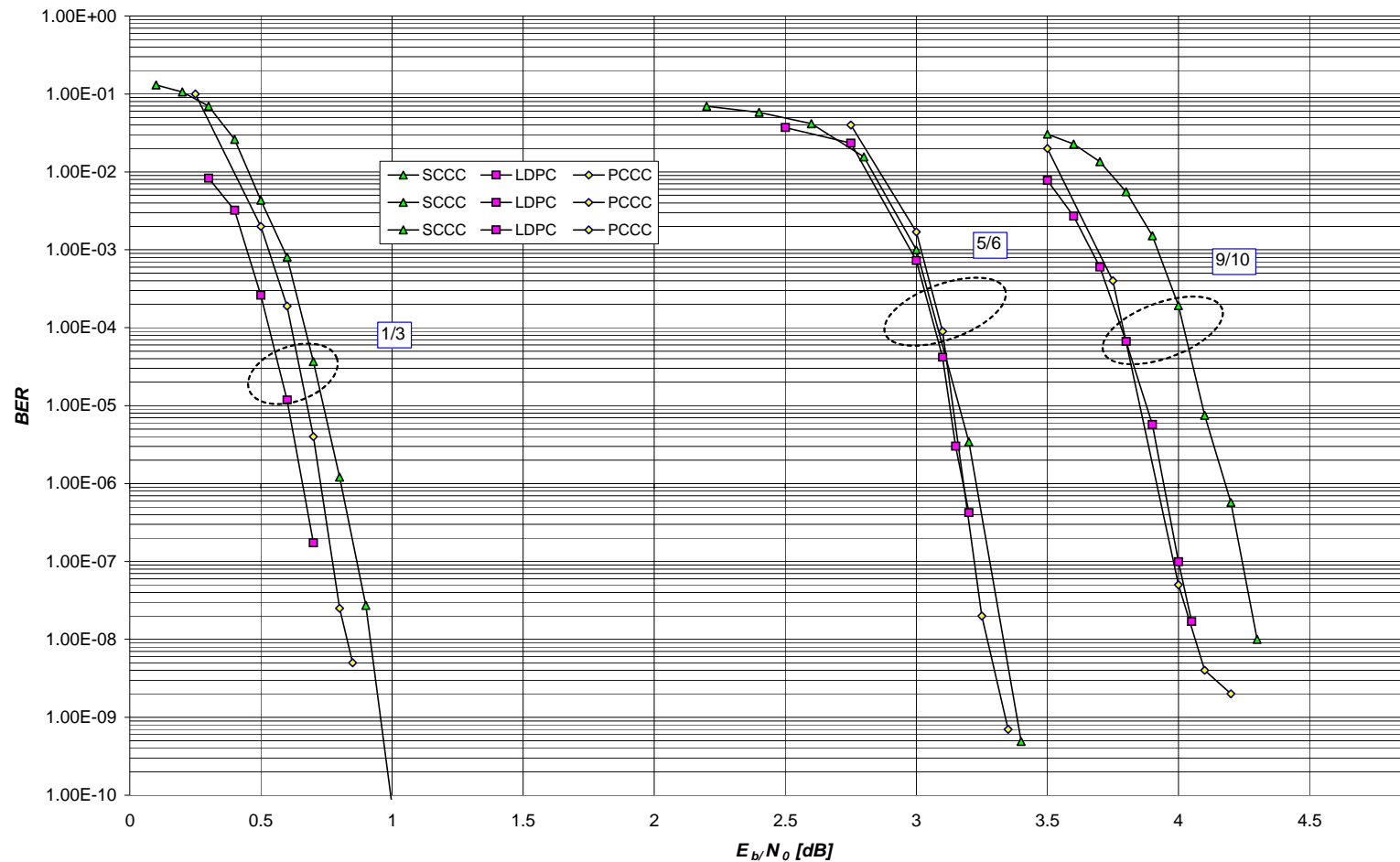Source of data for the TCM scheme: CNES

$-E_s/N_0 = E_b/N_0 + 10*\log(2*238/254)$ for 2 bits/channel case
$-E_s/N_0 = E_b/N_0 + 10*\log(2.5*238/254)$ for 2.5 bits/channel case
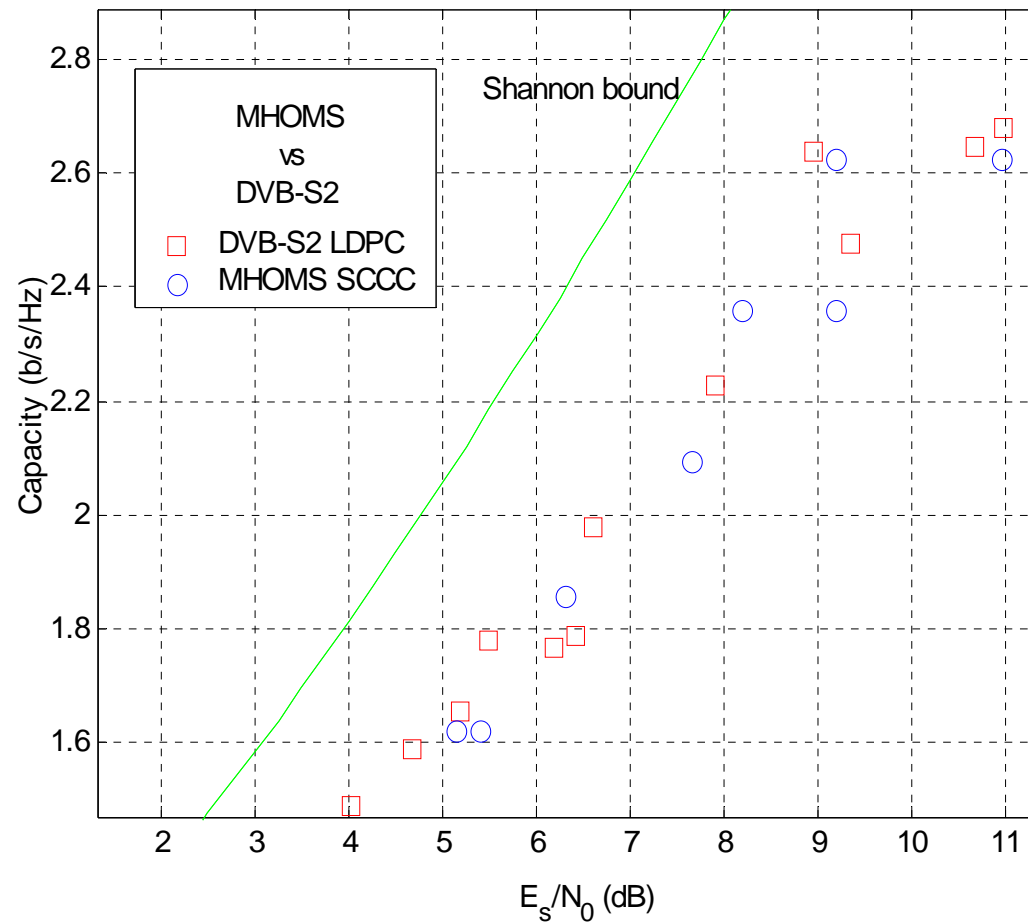
The performance gain of the SCCC w.r.t. the TCM scheme reduces by 0.15~0.2 dB at BER=10^{-6} as the slope of the SCCC BER curve is higher

BER performance comparison between LDPC, SCCC and PCCC

Simulation results, n=16,384

4PSK-modulation

Performance comparison between MHOMS and DVB-S2 LDPC at BER~10^{-9}

Envelope Equalisation & Amplifiers Pre-distorsion

- The use of amplifiers in saturation produces amplitude and phase distorsion plus spectral spreading.

- By means of pre-distorting the amplifer input signal, to compensate for the effects of the amplifier, the degradation on Bit Error Rate is minimised.

- By means of magnitude modulation of the input data stream, the spectral regrowth can be reduced.
  - Magnitude modulate each data prior to pulse shaping with the objective of generating a constant amplitude, bandlimited data stream at the input to drive the amplifier.
  - To be assessed for high order modulation schemes

Ground Station Equipment- High Data Rate Links

- ESA stations for EESS support are based on Cassegrain antennas with diameters of 15 and 13.5 meters.

- The input signal level to the multi-mode demodulator ranges from -50 to -10 dBm.

- Current multi-mode demodulators support unfiltered BPSK, QPSK and OQPSK.

- The minimum supported data rate is 30 Mb/s and the highest is 200 Mb/s (QPSK mode).

- The latter could be extended to 320 Mb/s (QPSK) and 160 Mb/s (BPSK) if needed.

- Data rates can be set in 1 Mb/s steps.

- It is possible to program baseband filtering and equalization. The minimum acquisition threshold is Eb/No=4 dB

- Differential decoding is also available (for both QPSK and BPSK)

- This equipment is installed in all stations supporting EESS payload telemetry - to date Kiruna and Svalbard.

Ground Station Equipment- Low/Medium Data Rate Links

- IFMS is used for data rates as high as 10 Mb/s.

- The input signal level ranges from -105 to -15 dBm.

- The IFMS implements residual and suppressed modulation schemes, including BPSK, QPSK, OQPSK (all three with and without ECSS specified SRRC filtering), and GMSK as of this year.

- The minimum data rate for suppressed carrier is 100 bps and the acquisition threshold is $E_b/N_o = -1.5$ dB

- Data rates can be set in 1 b/s steps.

- Differential decoding is also available (for QPSK, OQPSK and BPSK)

- This equipment is installed in all ESA stations.

Conclusions (I)

Current Situation

- All candidates are compliant to the SFCG mask even in case of using a SSPA in saturation

- 4D TCM 8PSK with efficiency 2 b/s/Hz vs. OQPSK

  – Comparable in terms of occupied bandwidth.

  – Required Eb/No for a fixed BER is lower for 4D TCM 8PSK

  – OQPSK has the advantage that is currently supported by all EES ground stations around the world → good for interoperability.

- 4D TCM 8PSK with efficiency 2.5 b/s/Hz is better in terms of occupied bandwidth but requires more transmitted power.

Conclusions (II)

Future Missions

- Band Reallocation. If the mission requires more than 375 MHz, the solution is moving to the 25.5-27 GHz band.
  - This band provides 1500 MHz bandwidth
  - New developments (on-board and on-ground)
  - Additional propagation constraints
- SCCC codes with high order modulation schemes
  - Simple solution
  - Multiple coding rates are supported
  - Performance close to the Shannon limit
  - Frame compatibility to be assessed
  - Envelope Equalisation & Amplifiers Pre-distorsion techniques
  - High order Modulation: 8PSK, 16QAM, 16APSK, 32APSK